On the Gibraltar Current, the Gulf Stream, and the General Oceanic Circulation. By Dr. W. B. CARPENTER, F.R.S.

INTRODUCTION.

Though requested by the President of the Royal Geographical Society, more than two years since, to bring before it some of the results of the Deep-Sea explorations in which I have recently taken part, I have hitherto been restrained from doing so by an indisposition to offer a mere *résumé* of communications previously laid before the Royal Society, to which, as the promoter of our Expeditions, it was proper that our Reports of them should be addressed.

It has happened, however, that some views in regard to a General Oceanic Circulation, which were indicated—rather than developed—in my Report of the *Lightning* expedition of 1868, and in my portion of the Report of the *Porcupine* expedition of 1869, have called forth strong opposition from men of such eminence as Dr. Petermann, Mr. Croll, and my friend and colleague Professor Wyville Thomson; who agree in attributing to the Gulf Stream the whole of that amelioration of the North Polar climate, which I believe to be chiefly due to a much larger, though less obvious, movement of Oceanic water. Now, the results of the *Porcupine* expedition of 1870 have not only furnished what appears to me very cogent additional evidence in support of the view I advocate, but have enabled me to give it a much more complete development. For I believe myself now able to show that the Physical theory which accounts for the double current in the Strait of Gibraltar and the Baltic Sound, would justify the prediction that a like surface-flow and reverse under-flow must take place in any Ocean that is freely continuous between the Equator and either Pole; which is exactly what the Temperature-soundings of the *Lightning* and *Porcupine* Expeditions appear to me to indicate. And as the question thus raised is one of high scientific interest, as well as of great practical importance, I have thought that I could not do better than submit to a Society that specially concerns itself with Physical Geography such a formal exposition of my views, as may enable them to be fairly and fully discussed by those who are best qualified to do so.

I wish to state *in limine* that I claim no originality whatever in advancing the doctrine of a General Oceanic Circulation sustained by difference of Temperature. It has been hinted at by various writers, especially Prof. Buff and Capt. Maury, though, so far as I am aware, it has not been formally propounded by any.* If I have myself done

* It seems to be imputed to me, by Mr. A. Keith Johnston, jun., that I advance as my own what is really Prof. Buff's; whilst, on the other hand, I am rebuked by

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anything to strengthen the doctrine, it has been by showing that Polar Cold, rather than Equatorial Heat, is the *primum mobile* of this circulation; and further, by bringing a large number of phenomena, apparently unrelated, under the comprehension of the same Physical theory. If that theory can be shown to be in itself invalid or inapplicable to the facts of the case, and any more satisfactory explanation of those facts can be offered, I shall most gladly welcome it; having no other object to gain than the advancement of scientific truth. I ask only for a candid consideration of my arguments.

I.—Gibraltar Current.

1. The designation "Strait of Gibraltar" is usually applied to the space bounded on the west by Cape Trafalgar and Cape Spartel, and on the east by the two "Pillars of Hercules," namely, Jebel Tarik, or the Rock of Gibraltar, on the European side, and Jebel Musa, or Apes Hill, on the Barbary coast. And although, as Admiral Smyth has justly remarked,* we should be justified in extending the designation to the whole of that funnel-shaped entrance from the Atlantic which is bounded on the west by Cape St. Vincent and Cape Cantin, I shall use it on the present occasion in its more restricted sense, as the phenomena I am about to describe were all presented within the limits first mentioned. The length of the Strait is about 35 miles; its width, which is about 22 miles at its western entrance, gradually diminishes to somewhat more than 9 miles between Tarifa and Alcazar Point, and then increases until it reaches 12 miles between Gibraltar and Ceuta, eastward of which the Strait terminates abruptly in the wide basin of the Mediterranean. The deepest portion of the Strait is at its eastern extremity; its depth, between Gibraltar and Ceuta, reaching 510 fathoms, and averaging about 400. From this the bottom gradually, but irregularly, slopes upwards as far as the western extremity of the Strait, where the shallowest water is to be found. The depth of the northern half of the channel, between Capes Trafalgar and Spartel, scarcely anywhere exceeds 50 fathoms; whilst its southern half does not seem anywhere to reach 200, and may be considered to average about 150. On the Atlantic side of this "ridge" the bottom gradually slopes downwards, until it reaches, at 25 miles to the west, a depth about equal to that found between

Mr. Croll for adducing the authority of Humboldt and Prof. Buff in my support. In my *Lightning* Report ('Proceedings of the Royal Society,' Dec. 17, 1868, p. 187) I cited exactly what Prof. Buff has said on the subject; and every one is quite free either to assign the doctrine to him, or to make me entirely responsible for it.

* 'The Mediterranean,' p. 158.

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Gibraltar and Ceuta. This ridge, therefore, constitutes a kind of submarine "watershed," separating the inland basin of the Mediterranean from the great oceanic basin of the Atlantic.

2. Through the central part of this Strait a current almost invariably sets *eastwards*, or from the Atlantic into the Mediterranean. The *in*flow is most rapid in the narrower part of the Strait, where it usually runs at the rate of from *two* to *three* miles an hour; its rate sometimes rising to *four*, or even occasionally (as stated by Gibraltar pilots to Admiral Smyth) to *five*; whilst the current is sometimes so reduced in speed as to be scarcely perceptible, even giving place (though very rarely) to a contrary movement, or *out*flow from the Mediterranean towards the Atlantic. These variations are due to the action of winds and tides.

3. The constant current does not occupy by any means the entire breadth of the Strait, even at its narrowest part; its average width being there, according to Admiral Smyth, not more than 4 miles. On either side there is a stream, which when moving inwards is much less rapid, while its direction is periodically reversed under the influence of the lunar tide; so that at given times there are two lateral currents, the united force and amount of which, however, never approach those of the central inflow.

4. The rate of this central inflow diminishes immediately that it discharges itself into the Mediterranean basin, over the surface of which the Atlantic water spreads itself in virtue of its lower specific gravity. But the influence of the Gibraltar current is sensibly experienced along the Spanish coast as far as Cape de Gat, and along the African coast even as far as the Bay of Tunis; its force and direction, however, being greatly influenced by the winds that may happen to be prevalent.

5. The explanation of the Gibraltar current that has been most generally accepted is that originally given by Dr. Halley, who attributed it to the excess of evaporation from the surface of the Mediterranean over the whole amount of fresh water returned to it, either directly by rainfall, or by the rivers which discharge themselves into it; so that its level would be progressively lowered, if not kept up by the Atlantic inflow. The obvious objection to this explanation is, that as the water which passes off by evaporation leaves its salt behind it, and as the water which comes from the Atlantic brings its salt with it, there would be a progressive increase in the salinity of the water of the Mediterranean, which does not appear to be the case. This objection has been met by another hypothesis, viz., that although the *surface*-water of the

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Mediterranean does not show more than a slight excess of saltness, there may be a great increase in the proportion of salt held in solution in the waters of its abyssal depths; and it has even been surmised that a deposit of salt may be taking place on its bottom. This hypothesis seemed to derive support from the analysis made by Dr. Wollaston, in 1828,* of a sample of bottom-water brought up by Admiral Smyth from a depth of 670 fathoms, at a point about 50 miles eastward of the Strait; which analysis gave the extraordinary percentage of 17·3 parts of salt, with a specific gravity of 1·1288, the percentage in ordinary Sea-water being about $3\frac{1}{2}$ parts, and its usual specific gravity between 1·026 and 1·027. But as two samples of Mediterranean water, taken respectively from depths of 450 and 400 fathoms, at distances of 680 and 450 miles eastward of the Strait, showed a density but little exceeding that of ordinary Sea-water, it was pretty clear that the first result was anomalous; and that, in whatever way it was to be accounted for, it did not represent the general condition of the deep water of the Mediterranean.

6. In the course of our recent Explorations, we collected numerous samples of Mediterranean water from various points of the surface, and from various depths, ranging downwards to 1743 fathoms. Our researches were almost entirely limited to the Western basin; but our deepest sample was taken from the Eastern basin, about 60 miles beyond Malta. The Specific Gravity of each sample was determined at the time by Hydrometers specially constructed for the purpose, and specimens of the most remarkable were brought home for verification with the Balance. The proportion of Chlorine in each sample was determined by volumetric analysis, which can be readily carried on aboard ship; and from this the entire proportion of salt may be estimated with considerable exactness. The Physical and the Chemical method of ascertaining the density of each sample gave results which generally accorded very closely.—Similar determinations had been previously made in regard to samples of water taken in the Atlantic, both from the surface and from various depths down to 1095 fathoms, during the voyage of the *Porcupine* from Falmouth to Lisbon.

7. A comparison of these results leaves no doubt that there *is* an excess of salinity in the water of the Mediterranean above that of the Atlantic; but that this excess is slight in the surface-water, whilst somewhat greater in the deeper water. The salinity of the deep-water of the Atlantic differs very little from that of its surface-

* 'Philosophical Transactions,' 1829, p. 29.

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water, being sometimes a little greater, and sometimes a little less; but that of the deep-water of the Mediterranean is always in excess of the surface-water, the specific gravity increasing from 1·027 to 1·029, and the proportion of salt from about 3½ to about 4 per cent.*

8. Hence it seems a justifiable inference that the surface-evaporation from the Mediterranean exceeds the amount of fresh water returned into it; but that the increase of density which would result from the contiuual inflow of salt water to maintain the level, is in some way kept in check, probably through an efflux of the denser water by an under-current, as originally suggested by Dr. Smith, one of the earliest inquirers into the matter, in 1673. This is the view adopted by Sir John Herschel ('Physical Geography,' p. 28); and it has been considered to derive support from accounts that have been recorded from time to time, of vessels sunk in the narrower part of the Strait having floated up beyond its western entrance. But to these accounts no great importance is assigned by Admiral Smyth ('The Mediterranean,' pp. 154-157), who seems inclined to attribute these occurrences—if they really took place as narrated—to the action of the *lateral* surface-outflow.

9. The only objection that has been advanced, so far as I am aware, to the hypothesis of a westerly under-current, is based on the existence of the comparatively shallow "ridge," which (as already stated, § 1) crosses the western end of the Strait. The existence of this ridge, in the opinion of Sir Charles Lyell, "has dispelled the idea which was once popular, that there is a counter-current, at a considerable depth, in the Strait of Gibraltar, by which the water which flows in from the Atlantic is restored to that ocean." † But, as the depth of water on this "ridge" (§ 14) is much greater than the average depth of the British Channel, and as the under-current in the Baltic Sound flows very near the surface (§ 18), the validity of Sir C. Lyell's objection was fairly called in question by Captain Maury; who remarks: "To my mind, the proofs derived exclusively from reason and analogy are as clear in favour of this under-current from the Mediterranean, as they were in favour of the existence of Leverrier's planet, before it was seen through the telescope at Berlin." ‡

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* I made a point of obtaining a sample from the precise spot (indicated by the recorded latitude and longitude) from which Admiral Smyth's anomalous sample had been taken; and found it not more saline than several other samples of deep water. It appears, therefore, that the specimen placed in Dr. Wollaston's hands (which had been some years in Admiral Smyth's keeping) must have undergone reduction to less than one-fourth of its bulk.

† 'Principles of Geology,' 10th ed., vol. i. p. 563.

‡ 'Physical Geography of the Sea' (1860), pp. 194-196.

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10. I shall now concisely state the results of the inquiries made expressly to determine this point in the *Porcupine* Expedition of last summer.* These results were of a twofold character. It was our object in the *first* place to detect, if possible, by *mechanical* means, any movement which may be taking place in the deeper water, in opposition to the superficial inflow; and *secondly*, to determine by the temperature, the specific gravity, and the chemical composition of samples of water taken up at different points and from different depths, whether they belonged to the Mediterranean or to the Atlantic basin.

11. The *mechanical* method was entirely devised and carried out by my excellent friend, Staff-Captain Calver, with the practical ability for which he is distinguished. The *physical* and *chemical* observations, which were made under my own direction, gave results which harmonized completely with those of the mechanical, where both could be employed together, and supply a deficiency which the impossibility of applying the mechanical test on the uneven surface of the shallow ridge would otherwise have left in the proof of the outflow of Mediterranean water over it (§ 14).

12. Our investigations were first made in the mid-stream between Gibraltar and Ceuta, at nearly the narrowest part of the strait, and over a bottom of more than 500 fathoms' depth. It was conclusively proved by the action of Captain Calver's "current-drag" upon the boat from which it was suspended:—

(*a.*) That the current at 100 fathoms' depth flows *in*wards at less than half the rate of the surface-current.

(*b.*) That at 250 fathoms the direction of movement is completely reversed, the existence of an *outward* current being demonstrated by the dragging of the boat in direct opposition to the strong surface-current.

(*c.*) That at 400 fathoms there is still an *out*ward movement, though at a reduced rate.

13. Again, it was found by examining samples of water taken from the surface, from 100 fathoms, from 250 fathoms, and from 400 fathoms respectively, that, whilst the first two had the characteristic temperature and density of Atlantic water, the last two had the characteristic temperature and density of Mediterranean water; and it was specially remarkable that, whilst both the latter presented an excess alike in specific gravity and in the proportion of their saline constituents, which clearly indicated their derivation from the

* The details of these inquiries are contained in the Report of the Expedition, presented to the Royal Society, Dec. 8th, 1870, and published in its 'Proceedings.'

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Mediterranean basin, the sample taken from 250 fathoms' depth was much denser than that taken from 400 fathoms.* It seems obvious that this heavier stratum could not be kept so near the surface, above a stratum of inferior density, by any other means than a *current* of no inconsiderable force.

14. Similar observations were afterwards carried on at the western extremity of the Strait, where its breadth is greatly increased, and its depth proportionably diminished. The soundings taken along the line of a transverse section between Capes Trafalgar and Spartel show a great inequality of the bottom; channels of from 150 to 190 fathoms' depth existing in the immediate neighbourhood of shallows less than 50 fathoms from the surface. As was to be expected from the greater breadth of this part of the Strait, we found the *in*current flowing at a much lower speed than at its eastern extremity, its rate being reduced from nearly 3 miles to little more than 1¼ mile per hour. The use of the "current-drag" at 100 fathoms' depth, in a part of the channel of which the depth was 147 fathoms, did not indicate any reduction in this rate; but a decided retardation showed itself when the current-drag was lowered to 150 fathoms, in a part of the channel of which the depth approached 200 fathoms. As Captain Calver deemed it inexpedient to lower the "current-drag" to a greater depth, since it would have been almost certain to "foul" on the rocky bottom, we were unable to ascertain by mechanical means that the stratum of water *immediately* lying over the ridge has the outward movement which it might be expected to show; but whilst the existence of such an *out*flow may be regarded as a necessary inference from the existence of a powerful outward under-current at the opposite extremity of the Strait, valid evidence in favour of it was afforded by the fact that the density of the water brought up from this stratum unmistakably indicated its derivation from the deeper part of the Mediterranean basin.

15. It is clear, therefore, that the water which has undergone concentration by evaporation is being continually carried back into the Atlantic by this westerly under-current, which causes it to

* It may be well for me to mention that this statement rests not on a single observation, but on multiplied observations. The facts were first noticed in our passage *into* the Mediterranean, when their significance was not understood, and no theory was built upon them. The information obtained during our Mediterranean cruise, led me to see the extreme importance of the fact, if it should be substantiated by further examination; and a second set of observations was accordingly made, with great care, on our return-passage through the Straits. The results of the two sets of observations were precisely accordant; and they have been further checked by the examination of samples of water from the 250 and 400 fathoms' depths, carefully preserved and brought home.

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move up a gradual incline from the eastern to the western extremity of the Strait, so that the excess of density in the Mediterranean water is thus kept within a very narrow limit.

16. The essential phenomena of the Gibraltar current having been thus determined, we have to consider how they are to be accounted for; in other words, to inquire what is the source of the power which gives motion to the vast body of water continually flowing *in*wards from the Atlantic, and which not only gives motion to the under-current flowing *out*wards from the Mediterranean, but draws up the heavier water from the depths of its basin to the comparative shallow of its limiting ridge. This question has been, I conceive, correctly answered by Capt. Maury,* on the assumption —which our inquiries have proved to be correct—of the existence of an under-current; the immediate force in each case being *Gravity*, and the remote cause which brings it into action being *Solar Heat*. As the surface-level would be lowered by the excess of evaporation, it can only be maintained by an *in*flow. But, on the other hand, the maintenance of the level whilst the density of the Mediterranean water is in excess, disturbs the equilibrium between the columns of water at the two extremities of the Strait, the heavier water of the Mediterranean overbalancing the lighter water of the Atlantic; and thus a portion of the former is forced *out*wards as an under-current, thus again producing a depression of the level, to be restored by a surface inflow from the Atlantic. Now, since the Atlantic water which enters the Mediterranean is in its turn subjected to loss by evaporation and consequent increase of density, the excess on the Mediterranean side is constantly kept up; whilst, on the other hand, in consequence of the vastness of the mass of water in the Atlantic basin, and the dilution it receives elsewhere, the discharge of the heavier water of the Mediterranean produces no perceptible increase in *its* specific gravity. And thus, as the lowering of the level and the disturbance of the equilibrium are being constantly reproduced, the superficial *in*flow and the deep *out*flow will be as constantly maintained by the force of Gravity.

Thus, let M and A represent two columns, the one of Mediterranean and the other of Atlantic water: the former limited in diameter, so that its level and density are sensibly affected by excess of evaporation; the latter practically unlimited, so that any exchange of its own water with that of the Mediterranean does not sensibly affect either its level or its density. The two columns being originally of the same height and density, and being, consequently,

* 'Physical Geography of the Sea' (1860), pp. 186-197.

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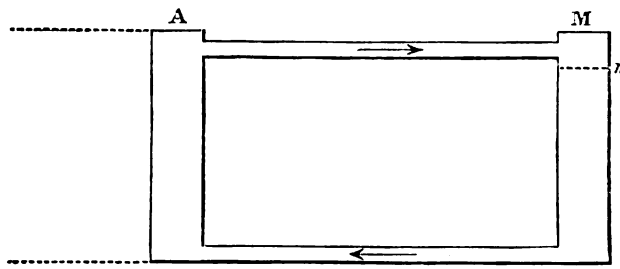
in equilibrium, let the *level* of the column M be lowered by evaporation to *m*; a surface *in*flow of salt water will then take place from



Diagrammatic Illustration of the Gibraltar Currents.

A to M for the restoration of the level. But since all the salt of the original Mediterranean column has been left in it, and the place of the *fresh* water it has lost is supplied by an influx of *salt* water, the whole quantity of salt in M will be increased, and thus its weight will come to exceed that of a corresponding column in A. This difference in the downward pressure of the two columns will cause an *out*flow of the lower portion of M into A, until the equilibrium is restored; but this outflow will in its turn renew the reduction in the level of M, which will be further lowered by the concentration of the water that has flowed in from A; and thus a fresh inflow will take place to keep up the level, and a further outflow to restore the equilibrium thus again disturbed.

17. It may conduce to the better understanding of this action, if we pause to consider what would be the result of a change in any of the conditions of its maintenance, thus:—

(*a.*) If the whole amount lost by evaporation from the surface of the Mediterranean were replaced by the *fresh* water of rain and rivers, there would be neither lowering of surface nor increase of density; consequently there would be *neither influx nor efflux* through the Strait of Gibraltar.

(*b.*) If, with the present excess of evaporation, the Atlantic were to supply *fresh* water instead of salt, there would be an *influx* through the Strait to the amount required to maintain the level; but there would be *no efflux*, since the equilibrium between the two columns would not be disturbed.

(*c.*) If, on the other hand, the quantity of *fresh* water discharged into the Mediterranean basin by rain and rivers were *in excess* of its evaporation, its level would tend to *rise*, whilst its density would tend to *decrease*. In that case there would be a *superficial efflux* of

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the lighter water of the Mediterranean into the Atlantic; whilst, as the equilibrium would be continually disturbed in the opposite direction (the Atlantic column being then the heavier), an *under-current* of the denser Atlantic water would flow *inwards*.

18. Now, this last hypothetical condition is precisely that of the Baltic in regard to the North Sea. The Baltic receives the drainage of one-fifth of Europe, and its evaporation is comparatively small; so that its level would be progressively raised, if the excess did not pass off by its three outlets—the Sound, the Great Belt, and the Little Belt—into the German Ocean. Now, just as the waters of the Mediterranean would gradually *increase* in saltness, if its density were not kept down by exchange with the Atlantic, so would that of the Baltic progressively *diminish* in saltness, by the washing-out of its shallow basin (so to speak) with river-water, if there were no return-current beneath, bringing back denser water from the German Ocean. But since we find, as a matter of fact, that its density is pretty uniformly the same, being about one-sixth that of ocean-water, it is obvious that there *must* be an under-current bringing back as much salt as is carried out by the surface-current. The force of this inferential proof could scarcely be increased by experimental verification. Such verification, however, has actually been obtained, as recorded by Dr. Smith, who first advanced the hypothesis of the Gibraltar under-current.* He states, on the authority of an intelligent seaman who took part in the experiment, that a boat having been taken into the mid-stream of the Sound, where it was carried along violently by the outward current, a bucket was sunk with a heavy cannon-ball to a certain depth of water, which gave a check to the boat's motion; and that on sinking the bucket still lower, the boat was driven to windward against the upper current. The surface-current seemed to be not more than four or five fathoms deep; and the under-current was found to increase in strength, the lower the bucket was let fall. This statement has recently been confirmed by Dr. Forchhammer;† who has obtained the comparatively dense water of the Kattegat from the bottom of the Sound, just as we obtained dense Mediterranean water from the deeper stratum in the Strait of Gibraltar. And he further mentions that a steamer having been sunk, some years since, by a collision near Elsinore, a diver who went down to save the passengers' goods found a strong current running towards the Baltic; and also that it is often observed that large deep-going vessels make their way

* 'Philosophical Transactions,' vol. xiv. p. 364.

† See his Memoir "On the Composition of Sea-Water," in 'Philosophical Transactions,' 1865, p. 231.

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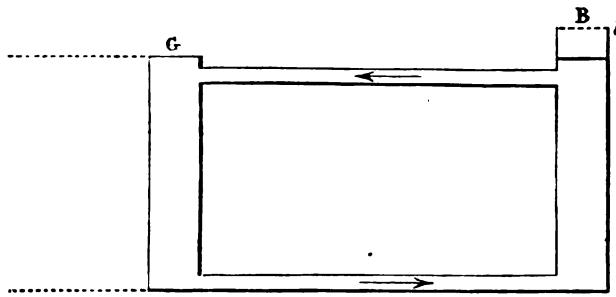
through the Sound against the surface-current, where smaller vessels do not succeed.*

19. The maintenance of this undercurrent in the Baltic Sound will be a necessary consequence of the constant inequality between the weights of columns of water of equal heights in the Baltic Sea and the German Ocean; not, as in the case of the Atlantic and the Mediterranean, through the increase of the specific gravity of the water in one column by continual concentration, but through the reduction in the specific gravity of the other by continual dilution.



Diagrammatic Illustration of the Baltic Currents.

Thus let B and G represent two columns, the one of Baltic, and the other of German Ocean water: the former limited in diameter, so that its level and density are sensibly affected by the surplus influx of fresh water; the latter practically unlimited, so that any outflow which takes place from the Baltic affects neither its level nor its density. The two columns being originally of the same height and density, and being consequently in equilibrium, let the *level* of the column B be *raised*, by an influx of fresh water, to *b*; this will cause a surface-outflow from B to G, for the restoration of the level. But since the *density* of the Baltic column has been *lowered* by admixture with fresh water, and a portion of its salt has been carried off by the surface-outflow, the restoration of the level will make the Baltic column the *lighter*; and the difference of downward pressure in the two columns will cause an inflow of the lower portion of G into B, until the equilibrium is restored. But this will, in its turn, renew the elevation in the level of B, which will be further raised by the continued influx of fresh water; and thus a renewed surface-*out*flow will take place to restore the

* This last circumstance has its parallel in the southward movement of icebergs, in opposition to the surface-drift of the Gulf Stream.

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level, and a renewed deep *in*flow to restore the equilibrium.—The same is doubtless true in regard to the Euxine, which is continually discharging into the ocean by the Bosphorus and the Dardanelles currents the excess of water which is brought into it by the Don, the Dnieper, and the Danube, but of which the density is constantly maintained at about two-fifths the standard of Ocean-water. And the like explanation will apply to the still stronger case of the Sea of Azof, in which salt is always found, though in small proportion, notwithstanding that it is continually discharging at the Strait of Yenikale the vast body of water brought down into it by the Don. If there were no reflux of salt water beneath the surface out-currents, each of these basins would in time come to be occupied by fresh water only.

20. Since, then, Captain Maury's doctrine proves applicable, *mutatis mutandis*, to cases of which the conditions are exactly the reverse of those on which it was based in the first instance, it seems to me to present a strong claim to unhesitating acceptance; and I shall now proceed to develop the same fundamental principle in a much more extensive form.

21. A little consideration will make it obvious that a like circulation must take place in *any* case in which a want of Level and a want of Equilibrium between two columns of water are constantly maintained, whatever may be the agency concerned in disturbing them; and I shall now show that a constant difference in Temperature will have exactly the same effect as alteration of bulk and density by evaporation or dilution.

22. Suppose two basins of Ocean-water, connected by a Strait, to be placed under such different climatic conditions, that the surface of one is exposed to the heating influence of Tropical sunshine, whilst the surface of the other is subjected to the extreme cold of the sunless Polar winter. The effect of the surface-*heat* upon the water of the tropical basin will be for the most part limited (as I shall presently show, § 40) to its *uppermost stratum*, and may here be practically disregarded. But the effect of surface-*cold* upon the water of the Polar basin will be to reduce the temperature of its *whole mass* below the freezing-point of fresh water;* the surface-stratum sinking, as it is cooled, in virtue of its diminished bulk and increased density, and being replaced by water not yet cooled to the same degree. This warmer water will not come up from below (as it must do when the entire surface of a pond or lake is acted on by

* Sea-water does not expand, like fresh water, below 39°·5; but continues to contract down to its freezing point, which, if the water be undisturbed, is as low as 25°.

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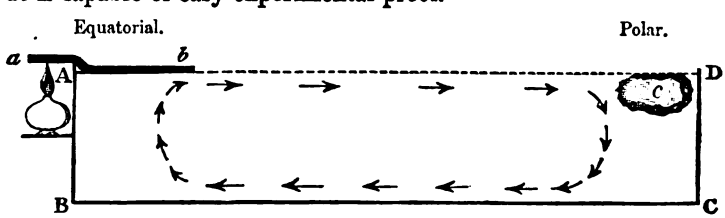
atmospheric cold), but will be drawn into the basin from the surface of the surrounding area; and since what is thus drawn away must be supplied from a yet greater distance, the continual cooling of the surface-stratum in the Polar basin will cause a "set" of water towards it to be propagated backwards (so to speak) through the whole intervening Ocean in communication with it, until it reaches the Tropical area. But since the *weight* of the Polar column undergoes no reduction with the lowering of its *level*, which results from the reduction of its temperature, the *in*flux of surface-water, which will take place from the Tropical basin to restore that level, will impart additional weight to the Polar column; and this will cause an *ef*flux of its cold deep water for the restoration of the equilibrium. So long, then, as the warm water which passes into the Polar basin from the Tropical is subjected to the cooling influence of its atmosphere, and is in its turn sent down to the bottom by the increase in its density, so long will the continual reduction of level keep up an influx from the Tropical basin; and so long as that influx is maintained, a corresponding efflux will take place from the bottom of the Polar basin into the bottom of the Equatorial. As the surface-water of the latter is constantly drawn off into the former, the water which has entered it from below is gradually lifted up by what follows it, and thus at last comes to the surface, where it is in its turn exposed to the heating influence of the Tropical sun, and is thence drawn off into the Polar basin, to repeat the same circulation. If the temperatures of these two basins were to be equalized, equilibrium would speedily be established through the whole system; but so long as one is heated (though only at the surface) and the other is cooled, so long will a Circulation such as I have described be maintained.—This is not a hypothesis merely, but is capable of easy experimental proof.



Experimental Illustration of the General Oceanic Circulation.

A B C D is a long narrow trough, with glass sides, filled with water nearly to its edge, as indicated by the dotted line A D. A t A a thick metallic bar, *a b*, is so fixed that one part of it lies along the surface of the water, whilst the other, which projects beyond

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the trough, is heated by a spirit-lamp placed beneath. At D a piece of ice, *c*, is wedged-in between the two sides of the trough. Thus the water in the trough is acted on by *surface-heat* at one end, like the water of the Equatorial ocean, and by *surface-cold* at the other, like the water of the Polar Sea. By the introduction of *blue* colouring liquid at the *surface* near D, and of *red* colouring liquid at the *bottom* near B, it is shown that a continuous circulation is kept up in the direction of the arrows:—the *blue* liquid, as it is cooled by the ice, at once descends to C, then travels slowly along the bottom from C towards B, gradually rises towards the heated bar, and thence creeps along the surface back towards D; whilst the *red* liquid first rises to the surface, then travels along it from A to D (taking the place of that which has descended), then itself descends to C on being cooled by the ice, returns along the bottom from C to B, and, lastly mounts again towards A.*

23. The case is not essentially altered by the existence of free communication between the two basins, through a large body of intermediate water; the principal difference in the result being that the movement in each direction will be slower, whilst it will affect a larger mass. The action of Cold on the surface-water of each Polar area will be exerted as follows:—

(*a.*) In diminishing the height of the Polar column as compared with that of the Equatorial, so that a lowering of its *level* is produced, which can only be made good by a surface-flow from the latter towards the former.

(*b.*) In producing an excess in the downward *pressure* of the column, when this inflow has restored its level, in virtue of the increase of Specific Gravity it has gained by its reduction of volume; whereby a portion of its heavy bottom-water is displaced laterally, causing a further reduction of level, which draws in a further supply of the warmer and lighter water flowing towards its surface.

(*c.*) In imparting a downward *movement* to each new surface-stratum as its temperature undergoes reduction; so that the entire column may be said to be in a state of constant descent, like that which exists in the water of a tall jar when an opening is made at its bottom, and the water which flows away through it is replaced by an equivalent supply poured into the top of the jar.

24. The ice-cold water thus pressed away from the Polar areas will travel along the floor of the deep Ocean-basins continuous with their own, beneath the warmer water which it encounters there, and with which it will undergo a certain intermixture at

* This experiment, by the kindness of Prof. Odling of the Royal Institution, was exhibited at the Meeting of the Royal Geographical Society.

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their plane of junction; so that, as every fresh arrival will take its place beneath that which has preceded it, there will be a gradual *upward* movement of Polar water as it approaches the Equator, until it comes under the direct heating influence of the Tropical sun, to be again drawn towards the Poles by the tractive agency already described.

25. Here, then, we have a *vera causa* for a *General Oceanic Circulation*, which, being sustained simply by the unequal distribution of Solar Heat, will be entirely independent of any peculiar distribution of land and water that does not prevent the free communication between the Polar and Equatorial areas, in their depths as well as at their surface.—That this agency has been hitherto so little recognised by Physical Geographers,* I can only attribute to the prevalence of the erroneous idea of a uniform deep-water temperature of 39°; of which idea the observations made in the *Lightning* Expedition of 1868, confirmed and extended by those of the *Porcupine* Expedition of 1869, have completely proved the fallacy. Until it is clearly apprehended that Sea-water becomes more and more dense as its temperature is reduced, and that it consequently continues to sink until it freezes, the immense motor power of Polar Cold cannot be understood. But when this has been clearly recognised, it is seen that the application of *cold at the surface* is precisely equivalent as a moving power to that application of *heat at the bottom*, by which the circulation of water is sustained in every Heating Apparatus that makes use of it.†

26. Let us now inquire how far this theory is borne out by facts. In the first place, there is now ample evidence of the passage of

* Mr. Croll ('Philosophical Magazine,' Oct. 1870), in arguing against the doctrine of a General Oceanic Circulation sustained by difference of Temperature, and justly maintaining that such a circulation cannot be produced by the application of Heat at the surface, has entirely ignored this agency of Cold. And, whilst invoking the authority of Sir John Herschel against the idea that differences in Specific Gravity can be the cause of Ocean-*currents*, he altogether loses sight of the fact that, when Sir John Herschel maintained this view, he was a believer in the prevalence of a uniform deep-sea temperature of 39°, and further, that his objection does not apply to the slow movement, imperceptible to ordinary observation, which I advocate as the only explanation that appears to me possible of the temperature-phenomena of the North Atlantic. When Mr. Croll shall have accounted for the undercurrents in the Strait of Gibraltar and the Baltic Sound on any other principle than that of difference in Specific Gravity, he will be entitled to call in question the power of such difference to operate in producing a General Oceanic Circulation. But as the doctrine given above has been accepted as valid by some of the most distinguished Mathematicians and Physicists of this country, I must decline to recognise Mr. Croll's right to assume its fallacy.

† In the large heating-apparatus that warms the building of the University of London, the water leaves the boiler at about 120° (Fahr.), and returns to it at about 80°. Thus a difference of 40° is here sufficient to maintain the circulation through an extensive range of pipes, in which there will be considerable retardation by friction and change of direction.

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Polar water at considerable depths beneath an upper and warmer stratum, not only into the Temperate but also into the Tropical zone. The indications of this fact previously obtained have been confirmed and extended, so far as regards the eastern part of the Atlantic, by the *Porcupine* Temperature-soundings of 1869; and also by the Temperature-soundings recently taken by Commander Chimmo and Lieut. Johnson in the Mid-Atlantic, as stated in my Report (pars. 113-119). And the Temperature-soundings recently taken by Commander Chimmo with the "protected" thermometers in Lat. 3° 18½′ S., and Long. 95° 39′ E., give 35°·2 as the bottom-temperature at 1806 fathoms, and 33°·6 at 2306 fathoms. Although the *Porcupine* temperature-soundings of 1870 were not carried down in the Atlantic to the great depths explored in the previous year, they brought into prominence this remarkable fact, that off the coast of Portugal there is a fall of *nine degrees* (namely from 49° to 40°) between 800 and 1000 fathoms; this being obviously the "stratum of intermixture" between the deep layer that has been cooled by the influx of Polar water, and the more superficial layer which has been heated by the Southern sun.

27. On the other hand, the surface-flow of Equatorial water towards the North Polar area is a fact universally admitted; and of its immense importance in moderating what would otherwise be the unbearable cold of that area, not the slightest doubt can be entertained by any one who makes himself acquainted with the evidence on this point recently collected by Dr. Petermann ('Mittheilungen,' 1870, p. 202). I do not in the least question the correctness of the conclusions which Dr. Petermann has drawn on this point from the mass of evidence which he has collected and correlated in his valuable Temperature-maps. What I question is the correctness of the doctrine that this north-east flow is *an extension or prolongation of the Gulf Stream*, still driven on by the *vis a tergo* of the Trade Winds,—a doctrine which (greatly to my surprise) has been adopted and defended by my colleague, Professor Wyville Thomson.* But whilst these authorities attribute the whole, or nearly the whole, of this flow to the true Gulf Stream, *I* regard a large part, if not the whole, of that which takes place along our own western coasts, and passes north and north-east between Iceland and Norway towards Spitzbergen, as quite independent of that agency; so that it would continue if the North and South American continents were so completely disunited, that the Equatorial current would be driven straight onwards by the Trade

* See his Lecture "On Deep-Sea Climates," in 'Nature,' July 28th, 1870.

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Winds into the Pacific Ocean, instead of being embayed in the Gulf of Mexico, and driven out in a north-east direction through the "Narrows" off Cape Florida.

28. To the *mere* Physical Geographer * it may perhaps seem of little importance which of these views is the correct one. The transfer of a vast amount of heat from the Equator towards the Poles by a continual movement of water being admitted on both sides, the question whether the *so-called* Gulf Stream which warms Iceland, Spitzbergen, and the Polar area generally, is, or is not, an extension of the *real* Gulf Stream which issues from the Narrows, may seem scarcely worth discussing. But any one who takes a *scientific* view of the matter must see that the question is one of the highest interest, from its relation to the general theory of Ocean Currents, past as well as present. For if the doctrine of a General Oceanic Circulation depending only on differences of Temperature be correct, it comes in as an important element in the study of all other great currents at the present time, and especially of those of the southern Oceans, which seem much less attributable than those of the northern to the *primum mobile* of the Trade Winds, and indicate a general "set" of warm surface-water towards the Antarctic Pole, as pointed out by Capt. Maury ('Physical Geography of the Sea,' pars. 748-750), which is particularly noteworthy in a broad band that occupies in the Southern Hemisphere a position closely corresponding in longitude with the so-called Gulf Stream between Iceland and Norway, and carries an almost Equatorial temperature as far South as lat. 40°. Further, the question is of yet greater importance in its Geological relations; since any circulation that has its origin simply in difference of Temperature must have been maintained throughout all geological epochs; and the formation of Glacial beds, marked by the presence of the marine types of Polar waters, may have been taking place at any time and in any part of the Equatorial Ocean, without any reduction of the land temperature. Whereas if these glacial currents are originally dependent upon the motion communicated to the true Gulf Stream (as Prof. Wyville Thomson maintains †), they would cease to flow over the deep bed of the Atlantic, if the stream were diverted by the free passage of the Equatorial current into the Pacific.

29. In order, then, that the various points of contrast between the two doctrines may be clearly understood, I shall state them separately and explicitly. Their divergence may be said to commence at that part of the North Atlantic, in which, according to

* See Mr. Keith Johnston, Junr., in the 'Academy,' December 15th, 1870, p. 70.
† See his Lecture "On Deep-Sea Climates," in 'Nature,' July 28th, 1870.

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the best authorities, the true Gulf Stream ceases to manifest itself as a definite north-easterly current; one large portion of it having been deflected southwards to return into the Equatorial current, whilst the remainder interdigitates with the opposing Arctic current, whereby its rate and temperature—already greatly reduced—are subject to such a further reduction, that, as Sir J. Herschel expresses it, the Gulf Stream *as such* is dispersed and destroyed.* This dispersion may be affirmed to be complete in about Lat. 45° N., and Long. 35° W.; to the north and east of which, according to the recently-published Admiralty Chart, no *movement* save a surface-drift is perceptible.† Between this part of the Atlantic and the western coast of Southern Europe, there is a region in which, as I shall presently show, there is no evidence of any other elevation of temperature than that which may fairly be attributed to the effect of the true Gulf Stream nearer its source, in heating the south-westerly winds that blow towards the whole Atlantic coast of Europe,—an effect very justly insisted on by Mr. Croll as an important element in the discussion of the total amount of work done by it. Passing from this *neutral* region, however, in which the Isothermal lines tend *southerly* rather than northerly, we find as we go Northwards more and more distinct evidence, from the *northerly* direction of the Isotherms, of the transference of heat, by a slow movement of water, in a north-easterly direction; this becoming so decided in the interval between Iceland and Norway, that the summer Isotherms—as shown in Dr. Petermann's Map for July—turn almost due north, and pass onwards in that direction, with more or less of an easterly bend, even beyond Latitude 75°. In connection with this phenomenon must be considered the under-flow of Polar water, which, as is admitted on both sides, brings back the surplus cold (so to speak) of the Polar area to the deep-sea bottom of the Equatorial zone.

(*a.*) Now on the one side the north-easterly flow of warm surface-water is affirmed to be a prolongation of the true Gulf Stream current, still urged on by the *vis a tergo* in which that current has its source, viz. the westward propulsion of intertropical water by the Trade Winds, constituting the Equatorial current; and the en-

* 'Physical Geography' (1861), p. 51. Sir John Herschel's statement as to the *thinning-off* of the Gulf Stream in this region has been fully confirmed by more recent observations.

† Of the prevalence of such a surface-drift there is ample evidence in the arrival of trees, fruits, and even floating shells (as *Spirula*) of the Tropics on the shores of the Hebrides, and the Shetland, Orkney, and Faroe islands. But of this drift the prevalence of south-west winds over that part of the Ocean seems a sufficient explanation.

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trance of this water into the Polar area will be always tending to produce an *elevation* of its level.—On the view I advocate, this north-easterly flow is regarded as due to the *vis a fronte* originating in the action of cold upon the water of the Polar area, whereby its level is always tending to *depression* (§ 22).

(*b.*) So, on the one side, the return underflow of Polar water is considered as dependent on the Gulf-Stream current and its north-eastern extension, the water of which would *raise* the surface-level of the Polar basin, if this were not kept down by an escape from below, which, in its turn, is drawn into the Equatorial area to keep up the level that would otherwise be *lowered* by the flowing off of the Gulf Stream.—According to the doctrine here propounded, the deep efflux of Polar water is considered as the *primum mobile* of a General Oceanic *vertical* Circulation, of which the north-east surface-flow is the complement; whilst the Gulf Stream is part of a local *horizontal* circulation, which is completed by the direct return of a large portion of it into the Equatorial current, while the portion which proceeds farther north ultimately returns in the Polar surface-currents, of which the principal keeps its way southwards between the coast of the United States and the Gulf Stream, back to its very commencement.*

30. In discussing this question, I shall first endeavour to show that the portion of the Atlantic which lies between the Azores and the coast of Southern Europe is *thermometrically* a *neutral region*; the surface-temperature of which is that which normally belongs to itself in virtue of its geographical position, undergoing no sensible modification from the influence of the Gulf Stream, except that which is due to the remote influence of south-west winds, and therefore affording no evidence of the extension of any prolongation of the Gulf Stream into its area. The careful correlation which I have made of the surface-temperatures, taken every two hours through the day and night in our last *Porcupine* Expedition, shows most unequivocally that the surface-temperature of the Mediterranean during the months of August and September is on the average *at least five degrees higher* than that of the eastern border of the Atlantic between the same parallels. As I have not the same positive information in regard to the relative *winter* temperatures of

* In speaking ('Nature,' July 28th 1870), of a deep indraught of cold *Antarctic* water as required to keep up the level of the Equatorial area which is lowered by the northward flow of the Gulf Stream, Professor Wyville Thomson does not explain how the accumulation of water in the *northern* hemisphere is prevented. Moreover a reduction of level will give rise to a *surface*-current, rather than to a deep indraught.

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these two Seas,* I must have recourse to a comparison between the temperatures of three stations on the Atlantic seaboard, and those of three stations within the Mediterranean in nearly the same parallels of latitude, as given in the Admiralty Pilot Charts for the Atlantic Ocean:—

COMPARATIVE TEMPERATURES.

ATLANTIC.

	Latitude.	Mean of Year.	November.	December.	January.	February.	Mean of Four Winter Months.
	° ′	°	°	°	°	°	°
Bordeaux	44 51	57·4	48	43	41	45	44·2
Lisbon	38 43	61·2	55	51	52	54	53·0
Cadiz	36 31	62·1	59	54	51	54	54·5

MEDITERRANEAN.

	Latitude.	Mean of Year.	November.	December.	January.	February.	Mean of Four Winter Months.
	° ′	°	°	°	°	°	°
Genoa	44 25	61·1	54	47	47	49	49·2
Palermo	38 7	63·0	59	55	51	51	54·0
Algiers	36 52	64·2	62	55	53	55	56·2

This comparison shows a decided excess in the Mean of the four winter months—as well as in the Annual Mean—in favour of the Mediterranean stations; and it seems a fair inference from this result that the temperature of the Atlantic seaboard of Southern Europe, between the parallels of 36° and 45° is *not perceptibly raised* by any afflux of Ocean water from a warmer source. It is no answer to this argument to urge that the winter temperatures of stations on the western shores of Europe are much higher than those of stations under the same parallels on the eastern sea-board

* Since this Paper was read, I have been referred by Mr. Prestwich to a Memoir by M. Aimé on the Temperature of the Mediterranean, in the 'Ann. de Chim. et de Phys.' for 1845; whilst the Hydrographer has been kind enough to furnish me with a set of Temperature observations in the Atlantic, contained in a Dutch work entitled 'Onderzoekingen met den Zeethermometer,' 1861. From these I have obtained the materials for the following comparison between the winter

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of America; because it is beyond all doubt that the winter temperatures of St. John's, Halifax, Boston, New York, and Washington, are all abnormally *depressed* by the Polar current which intervenes between those stations and the Gulf Stream.

31. As we proceed Northwards, however, the evidence of the mitigation of winter cold by the transportation of heat from a southern source, through the agency of ocean-water, becomes more and more apparent. The reduction in the surface-temperature of the sea is much more gradual than the difference of latitude would lead us to expect; and the climate of the neighbouring land, especially in winter, is correspondingly ameliorated. And though a part of this amelioration is doubtless attributable, as Mr. Croll has pointed out, to the warm south-west winds, which carry towards the north-east the heat they have drawn from the *true* Gulf Stream in latitudes below 30°, there is clear proof that this is by no means the whole explanation of the phenomenon. For, as will be presently shown (§ 33), the excess of warmth in the sea that laves the north-western shores of the British Isles is by no means confined to the surface, but extends to a depth which no mere surface-heating could possibly account for. The influence of this northerly flow of water bringing warmth from a southern source, is peculiarly well shown by a comparison of the temperature of Stromness, on the one hand, with that of Greenwich, which is nearly 7½° further south; and, on

temperatures of the Mediterranean at Toulon and Algiers, and those of the neighbouring part of the Atlantic under the same parallels:—

	N. Lat.	W. Long.	Temperature, deg. Fahr.			
			Dec.	Jan.	Feb.	Mean.
Toulon ..	43° 6′	5° 55′	57	53·8	53·4	54·7
Atlantic ..	43° to 44°	10° to 15°	55·2	55	53·8	54·6

	N. Lat.	Long.	Temperature, deg. Fahr.			
			Dec.	Jan.	Feb.	Mean.
Algiers ..	36° 52′	3° 2′ E.	60	57·6	56	57·8
Atlantic ..	36° to 37°	10° to 15° W.	61	58·8	58·8	59·5

The mean winter surface-temperature of the Mediterranean at Toulon is therefore exactly the same as that of the Atlantic under the same parallel; while that of the Mediterranean at Algiers is only 1° 7′ lower,—a difference quite insufficient to show that the Gulf Stream produces any thermal elevation of temperature in this part of the Ocean.

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the other, with that of Christiania and Stockholm, which are nearly in the same parallel of latitude with itself. All these stations are within the warming influence of the south-west winds, and they are all exposed to the moderating influence of a neighbouring sea. But whilst Stromness lies in the direct course of the north-east flow (commonly regarded as a continuation of the Gulf Stream), Greenwich, Christiania, and Stockholm, are secluded from its direct influence.

	Latitude.	Annual Mean.	Winter Temperature.				Mean of Four Winter Months.
			Nov.	Dec.	Jan.	Feb.	
	°	°	°	°	°	°	°
Stromness	58 58	46·2	43	41	38	38	40·0
Greenwich	51 30	49·0	43	41	35	37	39·0
Christiania	59 53	41·5	32	27	21	22	25·5
Stockholm	59 22	42·2	35	27	24	27	28·2

Here we see that, with a difference of latitude of nearly 7½°, the *mean annual* temperature of Stromness is only 2°·8 lower than that of Greenwich, whilst its temperature during January and February is decidedly milder. On the other hand, Stromness has an enormous advantage over Christiania and Stockholm in winter temperature, though the greater heat of their summer prevents this advantage from being so marked in the annual mean.

32. The evidence of the mitigation of Arctic cold by the transportation of Southern heat, in the north-east flow of Ocean-waters becomes stronger and stronger the further North the effects of that flow are traced. And I shall now endeavour to show that this mitigation is due to the *General Oceanic Circulation*, the existence of which it has been my aim to demonstrate on the ground of physical necessity, and the special applicability of which to the case in question I shall now point out.

33. The Temperature-soundings taken in the *Lightning* Expedition of 1868, and the *Porcupine* Expeditions of 1869 and 1870, clearly establish (1) that the north-east movement of Ocean-water is not a mere surface-flow, but extends to a depth of several hundred fathoms: and (2) that its transportation of warmth is even more marked in its lower than in its upper strata,—the surface-tempeture falling with that of the air, whilst the temperature of the deeper water suffers a much smaller reduction in its northerly course. These facts must, I think, become evident to any one who will carefully study the observations contained and digested in the

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'Preliminary Report of the *Porcupine* Expedition of 1869;'* and I shall here only give such a sample of those observations as will show their important bearing on the question before us. What may be designated as *serial* soundings having been taken at particular stations to ascertain the rate of descent of Temperature with progressive increase of Depth, I select for comparison the two series between which the difference of latitude was the greatest; namely, No. 87, which was taken at a point about 140 miles to the north-west of Scotland, and No. 42, taken at a point about 200 miles to the south-west of Ireland, the difference of latitude between them being rather more than 10°.

No.	N. Lat.	Temperature of Air.†	Temperature of Sea.					
			Surface.	100 Fath.	200 Fath.	300 Fath.	400 Fath.	500 Fath.
	° ′	°	°	°	°	°	°	°
87	59 35	54	52·6	47·3	46·8	46·6	46·1	45·1
42	49 12	66	62·6	51·1	50·5	49·6	48·5	47·4
Difference ..		14	10·0	3·8	3·7	3·0	2·4	2·3

Here we see that, with a reduction of 12° in the temperature of the Air at the northern station, there was a reduction of 10° in the heat of the surface-water; but that at 100 fathoms the difference is only 3°·8; and that the difference in the temperature of the deeper water between the two stations goes on decreasing, until, at 500 fathoms it is only 2°·3. Now, whether or not we attribute to the Gulf Stream the elevation of the surface-temperature in either or both of these cases,‡ it seems to me clear, from the very slight difference between the temperatures of the 400 fathoms beneath in latitudes 49° and 59° respectively, and from the great excess shown in the latter parallel above what may be considered as its normal isotherm, that the whole of this mass of water must have been derived from a southern source and must be travelling

* 'Proceedings of the Royal Society,' vol. xviii. p. 453.

† The temperatures of the air are not those of the particular hours at which the soundings were taken, but the daily averages in the two localities.

‡ I cannot myself doubt that the surface-temperature at No. 42, high as it may seem for the latitude, was due to the direct action of the summer sun, and was not imported from a southern source. For the weather had been very fine for some time previously, and the action of the sun very powerful; and the rate of declension through the first 100 fathoms from the surface downwards corresponded closely with that which was observed during the Mediterranean cruise of the *Porcupine* in 1870 (§40).

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slowly northwards. Further, a comparison of the serial sounding at Station 42 with the *bottom* temperature-soundings taken in the *Porcupine* Expedition of 1870 off the coast of Portugal, about 10° further south, affords similar evidence, in the correspondence of the rates of reduction from the surface downwards, that this northerly flow of a stratum at least 500 fathoms deep is traceable southwards to what I have designated the "neutral area" (§ 30).

N. Lat.	Temperature of Air.	Temperature of Sea.					
		Surface.	100 Fath.	200 Fath.	300 Fath.	400 Fath.	500 Fath.
° ′	°	°	°	°	°	°	°
49 12	66	62·6	51·1	50·5	49·6	48·5	47·4
About 39°	70	68·0	53·0	52·0	51·5	51·0	50·5

A comparison of these data brings into marked prominence the superior heating power of a deep mass of warm water, above that of a mere surface-layer. For we see that whilst the temperature of the upper stratum is rapidly cooled down in its northward passage, that of the 400 fathoms beneath it sustains comparatively little reduction. The thinned-out margin of the Tropical Gulf Stream would lose all its heat long before it reaches the Polar Circle; but the deep flow which carries northwards the warmth of a Temperate area yields it up far more gradually.

34. I cannot myself see how the movement of such a mass is to be accounted for on the hypothesis that its impelling force is derived from the surface-action of the thinned-out margin of the true Gulf Stream; but as my colleague, Prof. Wyville Thomson, interprets the fact (as to which there is no difference between us) in that sense, it is requisite for me to state why I cannot agree with him. "The basin of the North Atlantic," he says (*loc. cit.*) "forms a kind of *cul de sac;* and while a large portion of the Gulf-Stream water, finding no free outlet towards the north-east, turns southwards at the Azores, the remainder, instead of thinning-off, has rather a tendency to accumulate in the northern portions of the trough. We accordingly find that it has a depth, off the west coast of Ireland, of at least 800 fathoms, with an unknown lateral extension." Further, he says, in "the Shallow, including the Hebrides, the Orkney and Shetland Islands, and the Faroes, stretching westwards and northwards nearly to Iceland, the average depth is about 500 fathoms; and the Gulf Stream, which has a depth in these latitudes in summer of from 600 to 700 fathoms, occupies

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the whole of it, giving an abnormal temperature of something like 12°." Now, the temperature-soundings taken by Commander Chimmo in the neighbourhood of the Banks of Newfoundland clearly show that the thickness of the Gulf Stream does not there exceed 50 fathoms, and that it may be less. Thus, in Lat. 44° 3′ N., and Long. 48° 7′ W., the temperature of the surface-water being 61°, it was reduced at 50 fathoms' depth to 43°; whilst at 1000 fathoms it was 35°·5.* Between this part of the Atlantic and its north-eastern border, with which we are now concerned, there is an area, calculated by Mr. Findlay at 1,500,000 square miles, over which this thinned-out margin of the Gulf Stream is free to diffuse itself still more widely. And it is to me physically inconceivable that this surface film of *lighter* (because warmer) water should collect itself together again—even supposing it still to retain any excess of temperature—and should burrow downwards into the "trough," *displacing colder and heavier water*, to a depth much greater than that which it possesses at the point of its greatest "glory"—its passage through the Florida Narrows. The upholders of this hypothesis have to explain how such a re-collection and dipping-down of Gulf-Stream water is to be accounted for on Physical principles.

35. Now, the slow onward northerly movement of the whole mass of Ocean-water above that "stratum of intermixture" which intervenes between the upper Equatorial-polar flow and the deeper Polar-equatorial flow, is exactly what would be anticipated on the hypothesis of a Vertical Circulation, kept up by the opposition of Temperature between the Polar and Equatorial oceanic areas. Its rate, estimated by Admiral Irminger at from 1½ to 2½ miles per day,† is what may be expected on that hypothesis; whilst it is much less than that which the re-collected waters of the Gulf Stream ought to possess, in order to maintain their ground against the weight of colder water which they displace. I venture to urge, therefore, that the admitted existence of the northward "set" of this great body of warm ocean-water, taken in connection with the return-flow of Polar water already adverted to (§ 26), affords very strong evidence in favour of a general *vertical* Oceanic circulation.

36. Of such a Circulation the most remarkable example that has

* 'Proceedings of the Royal Geographical Society,' for February 8th, 1869.—The temperature recorded by Commander Chimmo at 1000 fathoms was 39°5; but this needs to be reduced by a correction of about 4° for the effect of pressure at that depth upon unprotected thermometers.

† 'Proceedings of the Royal Geographical Society,' vol. xiii. 1869, p. 227.

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yet presented itself was first discovered in the *Lightning* Expedition of 1868, and was more fully examined in the *Porcupine* Expedition of 1869; in which a great number of temperature-soundings were taken, that brought out very clearly the contrast in submarine climate produced by it in what I had ventured to designate as the Warm and Cold Areas.* The nature of this contrast will be readily understood from a comparison of the two serial soundings (Nos. 52 and 64) taken in the Cold Area, with the one already cited (No. 87) taken in the Warm Area: No. 52 being about 50 miles to the northward of No. 87; whilst No. 64, which was taken in the middle of the channel dividing the Shetland and the Faroe Islands, was nearly a degree northward of No. 52.

	No. 52. Lat. 60° 25'.	No. 87. Lat. 59° 35'.	No. 64. Lat. 61° 21'.
	°	°	°
Temperature at surface	52·1	52·6	49·7
,, at 50 fathoms	48·5	48·1	45·5
,, at 100 ,, ...	47·3	47·3	45·0
,, at 150 ,, ...	46·5	47·0	43·3
,, at 200 ,, ...	45·6	46·8	39·6
,, at 250 ,, ...	38·4	..	34·3
,, at 300 ,, ...	30·8	46·6	32·4
,, at 350 ,, ...	30·6	..	31·4
,, at 400 ,, ...	..	46·1	31·0
,, at 450 ,, ...	..	..	30·6
,, at 500 ,, ...	..	45·1	30·1
,, at 550 ,, ...	..	..	30·1
,, at 600 ,, ...	..	43·0	29·9
,, at 640 ,, ...	..	..	29·6
,, at 700 ,, ...	..	..	
,, at 767 ,, ...	..	41·4	

Between the temperatures of the surface and of the upper stratum down to 200 fathoms in Nos. 52 and 87, there is an extraordinarily close correspondence; but whilst, in the latter, reduction goes on gradually with the depth, there is in the former a sudden descent of nearly 15° between 200 and 300 fathoms; so that the temperature of the bottom at 384 fathoms is reduced to 30°·6. In No. 64 we find the temperature of the surface and of the upper stratum lower throughout, and the reduction commences earlier and goes on more gradually; but at 300 fathoms a temperature of 32°·4 was reached, and a further reduction showed itself with increase of depth, until at 640 fathoms a temperature of 29°·6 was marked. From these comparisons it seems clear, that whilst the upper stratum overlying the

* See the 'Preliminary Report' already referred to.

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Cold Area is a continuation of the warm flow which has made its way into this region from a southern source—rapidly losing heat as it passes northwards—the Glacial stratum beneath has been brought by some peculiarity of the bottom (like that which causes the deeper and heavier stratum of Mediterranean water to ascend the slope forming the bed of the Strait of Gibraltar, § 15) much nearer the surface than it lies elsewhere in that latitude.

37. That this Glacial stratum is really a *stream*, moving slowly onwards towards the south-west to discharge itself into the Atlantic basin, I cannot bring myself to doubt; although the point is contested by my Colleague, apparently on the ground that we did not trace its further course. "At the western mouth of the valley," he says, "the cold water is banked in and retained by the water of the Gulf Stream, which is slowly passing the entrance of the gorge; giving a repetition on a small scale of the curious phenomenon described by Professor Bache, off the coast of Massachusetts, as the 'cold wall.'" Now these two cases are by no means parallel. The Polar surface-current running southwards along the Atlantic sea-board of the United States, and the Gulf Stream running northwards, between which the "cold wall" intervenes, *move past* one another in opposite directions, as thus: $\overrightarrow{\text{Cold Wall.}}$ But the warm and cold streams in $\overleftarrow{\text{Cold Wall.}}$ the region which Professor Wyville Thomson and I have explored together, are moving *towards* one another in opposite directions, $\overrightarrow{\text{Warm}}$ $\overleftarrow{\text{Cold}}$; the *warm* stream from south-west to north-east, the *cold* stream from north-east to south-west. The *upper* layer of the warm stream passes *over* the cold stream, in virtue of its inferior specific gravity; and the analogue of the "cold wall" is here the "stratum of intermixture" between 200 and 300 fathoms' depth. Supposing that the cold stream were "banked in" by the *lower* stratum of the warm stream, its motion would be *checked* if the opposing forces of the two streams were equal, and *reversed* if the onward force of the warm stream were the greater. In either case the bottom would cease to show its glacial temperature; for the lower stratum in immediate contact with it would come to possess, if reduced to *stagnation*, the normal temperature of the latitude; whilst the *reversal* of the flow would bring up its temperature to that of the Warm Area. That we did not hit upon the outlet to this cold stream is, I believe, due to the smallness of the number of our soundings to the west of Long. 8° 10′, the most westerly point to which we traced it. It was at this point (No. 52) that there was the most distinct evidence of the *movement* of the stream, in the

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rounding of the gravel pebbles brought up from its bottom; and this seemed coincident with a narrowing of its channel, probably through the agency of a "middle bank."*

38. Here, then, we seem to have a sort of epitome, within the comparatively moderate depth of 384 fathoms, of that *surface* Equatorial → Polar flow, and of that *deep* Polar → Equatorial flow, which, in the great Oceanic basins, can only be substantiated by Temperature-soundings reaching to more than 1000 fathoms, but of which all such soundings that can be regarded as at all reliable, afford very distinct indications,† as I have shown in Pars. 118-121 of the 'Preliminary Report' of the *Porcupine* Expedition of 1869.

39. Having thus fortified my own position, by showing that the power I have invoked has a real existence and a most extended and varied operation, instead of being a figment of my own imagination (as Mr. Croll represents it ‡), I shall venture to attack the strong-hold of my adversaries, by showing that the Gulf Stream, at the point of its greatest "glory," can by no means claim the heating power which they assign to it.

Thermal Work of the Gulf Stream.

39. "From an examination of the published sections some years ago," says Mr. Croll, "I came to the conclusion that the total quantity of water conveyed by the Stream is probably equal to that of a stream 50 miles broad and 1000 feet deep, flowing at the rate of 4 miles an hour; and that the mean temperature of the entire mass of moving water is not under 65° at the moment of leaving the Gulf." § The correctness of this estimate has been already called in question by Mr. Findlay,‖ who has shown that it is by no means justified by the data supplied by the American

* I am authorised by Captain Calver, whose practical knowledge of all matters relating to currents entitles his judgment on this question to the greatest weight, to state that he entirely concurs in the interpretation I have given in Pars. 35–37 of the phenomena we have observed together.

† Since this Paper was read, I have received, by the kindness of Sir Henry Rawlinson, the following very interesting communication from Mr. Newall of Gateshead:—"In laying the Atlantic Cable of 1865, it is recorded that a red painted buoy, with a ball and flagstaff, was dropped on August 4th, in lat. 51° 28', long. 38° 42', to mark the broken end of the cable. This buoy was last seen by the West India Mail Steamer *Mexican*, on October 19th, 1865, in Lat. 42°, Long. 40°, when it appeared to be stationary; so that in seventy-six days it had travelled *nearly due south* about 600 nautical miles, or about 8 nautical miles a day. I presume that the buoy had been thus carried against the Gulf Stream by a strong undercurrent acting on the long buoy-rope."

‡ 'Philosophical Magazine,' October, 1870. See also the note *ante*, pp. 54, 55.

§ 'Philosophical Magazine,' February, 1870.

‖ 'Proceedings of the Royal Geographical Society,' February 8, 1869.

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surveyors. I have now to show that the data obtained during the *Porcupine* Expedition of 1870 may be fairly used as the basis of a still further reduction.

40. According to the mode of computation adopted by Mr. Croll, the *total amount of water* entering the Mediterranean from the Atlantic through the Strait of Gibraltar would be estimated by the sectional area of the channel between Gibraltar and Ceuta, and the rate of the surface-current, moving 3 miles an hour, at that point. Previously to our recent exploration, no one could have been justified in affirming that such an estimate is excessive; and yet we now know that it would have been egregiously wrong. For, as already shown (§ 12), the rate of inflow quickly diminishes from the surface downwards, so that at the depth of 200 fathoms there is probably "dead water"; whilst below 250 fathoms the movement is all *in the opposite direction*. I think that I should not under-estimate the real amount of the inflow if I were to take it at not more than *one-tenth* of the entire sectional area, moving at the rate of 3 miles per hour. No experiments have been made by the American surveyors of the Gulf Stream, so far as I am aware, for the purpose of ascertaining its rate and direction at different depths, in the narrowest—which is also the shallowest—part of its course, the strait between Cape Florida and the *Bemini* Isles; and until such experiments shall have proved the contrary, it may be affirmed that the assumption that the surface-rate prevails at even an inconsiderable depth,—much more that it extends through the entire sectional area,—must be considered as a pure assumption. For, it must be remembered, the action of the Trade Winds in producing the Equatorial Current is a *superficial* one; and there is no evidence that it sets in rapid motion any deep stratum of water. And even if the whole mass of water in the Narrows really flows in the same direction, there is every probability that the rate of its movement rapidly decreases from the surface downwards,*—the case being entirely different from that of a stream descending through a channel of which the bed progressively falls. But, further, the low temperature which has been ascertained to exist in its deepest stratum, is to me a very strong indication that there is *an undercurrent in the opposite direction*, bringing comparatively cold water into the Gulf of Mexico from the Polar current, which has been traced southwards to near the mouth of the Narrows. The existence of such an undercurrent is hinted at by the American surveyors themselves, in consequence of the distinct evidence they have obtained

* Here, again, I am permitted to cite the authority of Captain Calver in support of my position.

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of an almost glacial temperature beneath the heated waters of the Gulf Stream, both within the Gulf of Mexico and after its exit from the Narrows. In the present state of our knowledge, no one has any right to *deny*, any more than I have to *affirm*, the existence of such a reverse undercurrent; but, until its existence shall have been *dis*proved by actual observation, the analogy of other currents between gulfs or inland seas and the open ocean must be held to be in its favour.

40. In regard to the *average temperature* of the mass of moving water, the data supplied by the observations made last summer during the Mediterranean cruise of the *Porcupine* lead me to regard Mr. Croll's estimate as far too high. It seems based on the assumption that, in proceeding from above downwards, the temperature descends uniformly between the different points of observation—as in the section between the Florida Keys and the Havana—from 80° or 84° at the surface, to 60° at about 350 fathoms, and to 45° on the bottom at 845 fathoms. Now, three sets of observations in the Mediterranean, made at intervals of ten fathoms, show that the *superheating*, produced by the direct action of the sun upon the surface, is almost entirely limited to a stratum of *fifty* fathoms' depth, the descent of the thermometer being most marked in the first *twenty* fathoms, as shown in the following Table:—

	I.	II.	III.
	°	°	°
Temperature of air	74·3	75·0	78·3
,, of surface	69·5	74·5	77·0
,, at 10 fathoms	59·0	69·3	71·0
,, at 20 ,, ...	57·5	65·0	61·5
,, at 30 ,, ...	56·5	63·0	60·0
,, at 40 ,, ...	55·7	61·7	57·3
,, at 50 ,, ...	55·3	59·7	56·7
100	54·7	55·1	55·5

It is reasonable thence to infer (until evidence shall be adduced to the contrary) that a more rapid reduction from the surface-temperature would be found in the uppermost stratum of the Gulf Stream than in that which lies below it; so that any computation founded upon a uniform relation between temperature and depth is altogether erroneous. As the Mediterranean is altogether cut off from the Oceanic circulation, no data can be drawn from the temperature of its deeper water, which, from 100 fathoms downwards to the greatest depths we sounded—1508 fathoms in the western basin, and 1743 in the eastern—proved to be perfectly uniform.

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But, in our Atlantic soundings in a corresponding parallel of latitude, we found that, after passing through the heated surface-layer, there was a slow, nearly uniform, descent of temperature down to the "stratum of intermixture," in which there was another sudden drop of 10°. And, as it is clear from the reduction of temperature of the Gulf Stream to probably *less* than 45° at its bottom, that a stratum of water, cooled by admixture with a Polar current — whether moving inwards or outwards—underlies the warm stream, analogy justifies the suspicion that there may be a sudden reduction from 60° to 45° at no great depth below that at which the former temperature was obtained. At any rate it may be affirmed with confidence that, until a much more minute and accurate series of observations than any yet made* shall have determined the temperatures of different strata of the Gulf Stream, no reliable calculations can be even approximately made as to the amount of heat conveyed by it.

41. Since, then, Mr. Croll's estimate of the thermal work done by the Gulf Stream has been shown to be unreliable—in regard alike to the *amount of water* which daily flows outward through the Narrows, and the *amount of heat* which that water conveys,—and since the excess of his estimate (if the facts should prove to be accordant with the analogies I have adduced) will be in the *compound ratio* of the reductions which may have to be made in the two elements—I submit that no argument can be fairly based on that estimate against the doctrine of the General *vertical* Oceanic Circulation, on the ground that the Polar area is so effectually heated by the Gulf Stream that there is nothing left for any more general circulation to do.†

SUMMARY.

The *Physical Principles* on which the argument of the foregoing Paper is based, may be stated as follows:—

I. Wherever there is a *difference of level* between two bodies of water in communication with each other, there is a tendency towards the equalization of their levels by a flow of the *upper stratum* of the higher towards the lower.

II. So long as the difference of level is maintained, so long will this flow continue; and thus any agency which constantly lowers

* I am justified by the information I have personally received from Mr. Hilgard, under whose direction the observations above cited were made, in affirming that the Temperatures taken at considerable depths are by no means to be relied on, and that the whole of this work has to be done over again with *protected* Thermometers, such as were used in the *Porcupine* Expeditions.

† See his Paper "On the Physical Cause of Ocean Currents," in 'Philosophical Magazine,' October, 1870.

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the level of one body of water below that of the other (unless it directly antagonize the downward pressure of the higher water *), will keep up a constant flow from the higher towards the lower. This constant *tendency to equalisation of level* will restrain the actual difference within very narrow limits; and the movement, when there is free communication, will be proportionally slow.

III. Wherever there is a *want of equilibrium*, arising from *difference of density*, between two bodies of water in communication with each other, there is a tendency towards the restoration of equilibrium by a flow from the *lower stratum* of the denser column towards that of lighter, in virtue of the excess of pressure to which the former is subjected.

IV. So long as a difference of density continues to exist, so long will this flow continue; and thus any agency which constantly produces a fresh disturbance of equilibrium, whether by increasing the density of one column or by diminishing that of the other, will keep up a continuous flow from the denser towards the less dense. This constant *tendency to restoration of equilibrium* will keep the actual difference of density within definite limits.

V. If there be at the same time a *difference of level* and *an excess of density in the shorter column*, there will be a simultaneous tendency to the equalization of the *level* by an *upper flow from the higher to the lower*, and to the restoration of the *equilibrium* by an *under flow from the heavier to the lighter column.*

VI. So long as the *difference of level* and the *difference of density* are maintained, so long will the flow continue in each direction; and thus a *Vertical Circulation* will be kept up by any constant agency which alters at the same time the level and the density; provided that the excess of density always remains on the side of the lower column.

VII. The rate of flow, where it is not confined within narrow limits, will depend simply on the amount of disturbance, in the one case of *level*, and in the other of *density*; and when this disturbance is small, so as to be counteracted almost as soon as it takes place, the movement may be so slow as to be almost imperceptible, though not less real and effectual. But if the communication between the

* Thus, it has been shown by Archdeacon Pratt ('Phil. Trans.,' 1859), that in consequence of the local attraction produced by the high land of Asia, with nothing but Ocean to the southward, the Sea-level at the mouth of the Indus is no less than 515 feet above that at Cape Comorin.—So, again, if barometrical pressure be *permanently lower* over any Oceanic area, than on other parts of the surface, there will be a *permanent elevation* of the water-level in that area, but *no current*; equilibrium being there maintained when the *excess* of Water-pressure is equal to the *deficiency* of Air-pressure.

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two bodies of water take place through a long narrow channel, the rate of movement will increase so as to produce a decided current in each direction; since the moving force, which in the former case is diffused through a vast body of water, is here brought to bear upon a limited amount, and will act as a *constantly accelerating* one, increasing the rate of motion until any further augmentation is checked by opposing forces.

The *application* of the foregoing Principles to the particular Cases discussed in the Paper is as follows:—

VIII.—A Vertical Circulation is maintained in the Strait of Gibraltar by the *excess of evaporation* in the Mediterranean over the amount of fresh water returned into its basin, which at the same time *lowers its level* and *increases its density*; so that the *surface-inflow* of *salt* water which restores its level (exceeding by the weight of salt contained in it the weight of fresh water which has passed off by evaporation) disturbs the equilibrium and produces a *deep outflow*, which in its turn lowers the level.—The same may be assumed to be the case in the Strait of Babelmandeb.

IX.—A Vertical Circulation is maintained in the Baltic Sound by an *excess in the influx of fresh water* into the Baltic; which at the same time *raises its level* and *diminishes its density*, so as to produce a *surface outflow*, leaving the Baltic column the lighter of the two, so that a *deep inflow* must take place to restore the equilibrium.—The same may be assumed to be the case in the Bosphorus and Dardanelles.

X.—A Vertical Circulation must, on the same principles, be maintained between Polar and Equatorial waters by the difference of their Temperatures: the level of Polar water being reduced, and its density increased, by the surface-*cold* to which it is subjected, whilst a downward motion is also imparted to each stratum successively exposed to it; and the level of Equatorial water being raised, and its density diminished, by the surface-*heat* to which it is exposed. (The first of these agencies is by far the more effective, since it extends to the *whole depth* of the water, whilst the second only affects, in any considerable degree, the *superficial stratum*.) Thus a movement will be imparted to the upper stratum of Oceanic water from the Equator towards the Poles, whilst a movement will be imparted to the deeper stratum from the Poles towards the Equator.

XI.—Of such a *Vertical Circulation* in the general body of Oceanic water we have evidence, on the one hand, in the *northerly* movement of the upper stratum, *of several hundred fathoms' depth*,

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which carries the temperature of a warmer region into the Arctic circle (§ 33); whilst, conversely, there is now a large body of evidence as to the *general prevalence*, over the deep-sea bottom, of *a temperature not many degrees above the freezing-point of fresh water*, which cannot be accounted for in any other way than by an under-flow of Polar water towards the Equator. Further, under particular circumstances, a yet greater degree of cold is brought by Glacial currents into the Temperate zone (§ 36): thus giving distinct indication of a general movement of deep water from the Poles towards the Equator.

XII.—Lastly, it follows, if the foregoing doctrine be correct, that the General *vertical* Oceanic Circulation is the great agent in moderating the extreme cold of the Arctic basin; the water which flows towards it being not so much propelled into it by the Gulf Stream, as drawn into it from an area of which the ordinary temperature is little, if at all, above the normal. On the other hand, the Gulf Stream forms part of a *horizontal* or *superficial* circulation in the North Atlantic, of which the Trade Wind constitutes the *primum mobile:* a large part of its flow returns directly backwards into the Equatorial current, thus completing the *shorter* circulation; whilst the portion which passes northwards ultimately returns in the *superficial Polar currents* with which it interdigitates, —one of these currents being sufficiently powerful to maintain a distinct course back to the exit of the Gulf Stream, where its deeper portion not improbably re-enters the Gulf of Mexico as a reverse under-current through the Narrows.

CONCLUSION.

No one can be more sensible than I am myself that the General Doctrine propounded in this Paper cannot claim to be accepted as an established truth, until it shall have been tested by a vast number of observations, carefully carried out in various parts of the globe. But, if it should be thus substantiated, it will afford a more scientific basis for the study of Ocean-Currents than has yet been laid, and will thus tend to the improvement of Hydrography and Navigation. It may be hoped, therefore, that the systematic prosecution of observations upon the Temperature and Movement of the different strata of the ocean may henceforth be considered as a part of the regular duty of the British Navy,—the world-wide distribution of which gives to this country special facilities for cultivating this branch of inquiry, whilst laying upon it the special obligation of using those facilities in the interest of all nations.

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Supplemental Note.—In an Address delivered before the St. Louis (U. S.) Historical Society on the 10th December, 1868, upon the "Thermometric Gateways to the Pole," Captain Silas Bent not only attributes the mild winters of Marseilles, Genoa, and Naples to the heating influence of the Gulf Stream, "which, as a surface-current, flows constantly into the Mediterranean through the Strait of Gibraltar," but goes on to make the following curious assertion:—"Pursuing these reflections, this matter presents a phase of international importance which, were it not for the inhumanity of possessing such a power, might place the whole of Europe at the mercy of this country. For, admitting that Europe derives its mild climate from the Gulf Stream, which no one now, I believe, disputes, then to divert this stream from its present direction, would be to bring the whole of Europe at once, so to speak, to its normal climatic condition: that is, France and Austria would have the climate of Canada; and England, Germany, and Northern Europe would become a frozen wilderness, such as British America and Labrador. To accomplish this, the possession of the Isthmus of Panama, and the expenditure of two or three hundred millions of dollars in the excavation of a sufficient width and depth of the rock only, that intervenes between the Carribean Sea and the Pacific, and the opening of a small sluice through the soil, to afford a beginning for the passage of the water from ocean to ocean—and but a short time would probably elapse before the channel would be large enough to give a new outlet to the equatorial waters of the Atlantic, and thus cut off that excess which now goes to make the Gulf Stream." Now that the temperature of the Mediterranean owes nothing whatever to heat carried into it by the Gulf Stream, may be considered as demonstrated by the fact that in summer the surface-current in the Strait of Gibraltar is *decidedly colder* than the surface-water of the Mediterranean; and that in winter it is *not at all warmer*. Further, if the doctrine above advocated be correct, the complete diversion of the Gulf Stream would produce very little deterioration in the climate of North-Western Europe, the amelioration of which is mainly dependent upon the general Oceanic circulation. In threatening us with the reduction of our winter temperature to that of Labrador, Captain Bent has quite lost sight of the consideration stated at the end of par. 30.

Mr. A. G. FINDLAY said, about eighteen years ago ('Journal of the Royal Geographical Society,' 1853, pp. 217-242), he had endeavoured to demonstrate before the Geographical Society—a little more clearly than had been done previously—that, in each ocean, currents revolved around a central area, the

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Gulf Stream being the most remarkable of such currents, and that the general cause of all *surface*-currents could be attributed to the action of the prevalent winds. There is a Gulf Stream in every ocean; though, from the configuration of the land, and other causes, these great streams may not be so manifest in other oceans as in the North Atlantic. When, by the direction of the United States Government ten or eleven years ago, the narrowest part of the Gulf Stream was examined, figures were obtained which shut out all idea of its ever reaching our shores as a heat-bearing current. In the narrowest part, certainly not more than from 250 to 300 cubic miles of water pass per diem. Six months afterwards that water reaches the banks of Newfoundland, and nine or twelve months afterwards the coast of England, by which time it is popularly supposed to cover an area of 1,500,000 square miles. The proportion of the water that passes through the Straits of Florida will not make a layer of water more than six inches thick per diem over such a space. Every one knows how soon a cup of tea cools, and yet it is commonly imagined that a film of only a few inches in depth, after the lapse of so long a time, has an effect upon our climate. There is no need for calculations; the thing is self-evident. Although there may be no difficulty in attributing most of the well-known surface-currents of the ocean to a specific cause, such as the action of wind, yet this can only refer to the upper strata, not more than one-tenth of the entire depth. Of the lower beds we are in almost total ignorance; and it is only of late that we have acquired some amount of exact knowledge, not sufficient, as he believed, to establish a theory of general circulation, and yet, such a theory would seem to be an absolute necessity. The ocean is like the atmosphere; every part of it is intermingled in the course of ages. This can be proved mechanically, chemically, and biologically. All over the globe a surface-action on the sea can be traced, and there must be compensation somewhere. Again, if observations for specific gravity are taken at a certain depth below the surface, beneath the action of the sun, the falling rain, and the freezing ice, a wonderful uniformity is found all over the world. It is impossible that this uniformity should exist unless there is circulation. Thirdly, animals without power of voluntary locomotion exist over large areas on the bed of the ocean, and if the waters do not move they would starve. With regard to the depth of the Ocean he would adduce the following considerations. After the earthquake at Simoda, in Japan, on December 23, 1854, the tidal gauge at San Francisco was oscillated in a most remarkable manner, and it was subsequently agreed that it must have been due to the earthquake travelling across the Pacific in eighteen hours. Mathematicians have calculated that the size of a wave regulates its velocity, and the size of this wave demonstrated that the depth of the Pacific Ocean was about 2400 fathoms; and that is the real depth, since discovered, of that ocean. If, then, a wave, moving on the surface, is regulated by the depth of the ocean, there must be some connection between the bottom and the surface. The very interesting question of the Gibraltar and Mediterranean currents has occupied attention for a long period; and 150 years ago the lower outward current was inferred to exist in the Strait; an old evidence of it is cited of a vessel fired into (in 1712) and sunk in the middle of the Strait of Tarifa, which came ashore at Tangier, to the westward. On another occasion, in the Straits of Gibraltar, a vessel sunk off Ceuta, and she turned up off Tarifa on the other side, so that she must have gone across the Straits in the teeth of the stream. This was evidence, certainly, of an outward current. The expedition under Dr. Carpenter had brought much light on these subjects, but he thought that there would be some difficulty in attributing these opposing currents in the Strait entirely to a want of statical equilibrium. Because the same cause acted in a reverse direction in the eastern Straits of the Mediterranean; here the lower salt water flowed eastwards, and the upper

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and fresher water constantly flowed to the westward. The subject is now assuming new importance, and he hoped that Dr. Carpenter and his co-adjutors will be enabled to make still further experiments in the same direction.

Mr. F. GALTON said he should be glad of further evidence that the causes assigned by Dr. Carpenter were adequate to produce a current as powerful as that in the Straits of Gibraltar. In respect to the circulation undoubtedly caused by the difference in specific gravity of two adjacent columns of water, he could not but remark that, so far as that difference was created by unequal temperatures, the beautiful model exhibited in support of the theory, showed the resultant circulation to be exceedingly sluggish. This was the more striking, because the temperatures at the two ends of the model differsd extremely. Dr. Carpenter, however, in the earlier part of this memoir, had ascribed the Gibraltar current more especially, to the inflow of water from the Atlantic, to supply the lower level of the Mediterranean, caused by its more rapid evaporation. He did not think it likely that a current of some 60 miles in length running at 3 miles per hour could be principally maintained by those means, unless there should be a considerable difference of level between the two seas. He therefore asked Dr. Carpenter what the difference of level was at the two ends of the Straits of Gibraltar?

Mr. J. BALL said, no doubt the experiment had proved that, under certain conditions, an interchange will take place; but in the actual ocean a multitude of causes are at work, and it is by the combined, or contrasted action of these causes, that the phenomena occur. Sufficient stress had not been laid upon the vast amount of evaporation, and the consequent actual diminution of the height of the sea, in tropical regions. That diminution cannot be less than six feet per annum. The moisture carried northward and southward, and deposited in the rainy zone, is also a displacement of enormous bodies of water. These were causes of motion in addition to the mere difference of temperature. The North Atlantic circulation must be considered as very different from that of the other great oceans; for the North Atlantic is, in fact, a closed gulf, as it cannot be supposed that Behring's Strait exercises any material influence upon it. The subject was one of immense importance, and however valuable the contribution that Dr. Carpenter had made to it, all must reserve to themselves the right to admit any other explanation of the phenomena which may be given in future.

Admiral Sir EDWARD BELCHER said it was a curious fact known to nautical men, that for the last hundred years not twenty ships of the Navy of much draught of water have succeeded in beating round from Gibraltar westward within the line of this so-termed counter-current. Dr. Carpenter seemed to have lost sight of the fact that there is an ebb and flood tide at Gibraltar; and that the rise and fall is about 2 feet 6 inches. Probably the experiments he had made were not calculated exactly at high water. When Captain Smyth made his experiments there, he succeeded in obtaining results which showed that a counter-current did exist, but his instruments did not enable him properly to prove it. By being mixed with mud, of course the specific gravity of the water might be increased, and such a mixture may have something to do in producing the under-current. The heat of the Mediterranean surface is not sufficient to account for the immense evaporation. The greater part of the evaporation, he believed, takes place on the surface of the rocks which are exposed to the sun's rays. At Cape de Verd the current flows at the rate of 5 miles an hour; and on one occasion, in a perfect calm, he put thermometers over at 20 fathoms, 50 fathoms, 100 fathoms, and 500 fathoms, with a *baréca* and flag attached to each. At the end of one hour all the *barécas* and the ship were in the same relative positions as when they were laid down, showing that down to 500 fathoms the current ran at the same velocity as at the surface.

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Professor WILLIAMSON said it was quite in accordance with physical laws, that water which becomes heavier by concentration should flow in the opposite direction to a lighter current, but it was reserved for Dr. Carpenter's beautiful experiment to give a decisive proof of it.

Admiral OMMANNEY asked if Dr. Carpenter had ascertained whether or not it was true that *Mediterranean* water passes out by the coast of Spain, while *Atlantic* water flows in by the coast of Marocco? The current running in by the coast of Marocco is much more rapid than that running out by the coast of Spain. The influence of the inflowing stream is very soon lost after it passes Gibraltar. The water at Cadiz is influenced by the number of rivers from the surrounding country. When, on one occasion, he was lying in the Bay of Cadiz, his launch was blown out to sea, and some time afterwards it was picked up in the Straits.

Mr. LAUGHTON thought there were two or three facts connected with the experiment they had witnessed which militated strongly against its application to the circulation of the water of the ocean. The circulation in the trough was entirely in vertical planes, the cold water running along under the hot, without any approach on the top to a horizontal circulation. Under no circumstances would the cold water flow along one side of the trough and let the hot water flow along the other. The circulation in the ocean, however, is horizontal in many instances. In the North Atlantic the hot water runs up towards the north on the east side, but on the coast of Greenland, and down Baffin's Bay, a strong cold current flows, which falls into the warm stream at the Banks of Newfoundland, and so makes a complete horizontal circulation. The Gulf Stream runs towards the north, while the North African current flows towards the south; and the current on the east coast of Africa runs in an opposite direction to that on the coast of Australia. In all oceans, without exception, there is a horizontal circulation. He did not deny that there is also a vertical circulation, but he was of opinion that it is extremely slow,—so slow as to have no effect on what people interested in navigation understand as currents. It took the best part of an hour for the blue to get from one end of the trough to another, yet there can be no doubt that the differences of temperature were much more extreme than were ever found in nature.

Dr. CARPENTER, in reply to the various objections, said the rapidity of the current in the Straits of Gibraltar might be accounted for by the fact that water always ran more swiftly through a narrow throat than through a wide channel. No one could be more sensible than himself of the fact that he had merely broken the ground of a wide field of inquiry, and he was prepared to represent to the Admiralty that at least six months' work would be required thoroughly to examine the Gibraltar currents alone. No doubt it was the difference of the tides that caused the discrepancy between the two sets of observations. He had obtained very distinct evidence from the temperatures that the surface-current of Mediterranean water flows out along the coast of Spain, while the Atlantic water flows in along the coast of Marocco. Horizontal circulations, he believed, were due entirely to the prevalent winds, the trend of the land, and other causes acting only on the surface. In the experiment he had displayed to the meeting, the differences of temperature were not so great as those to be found in nature. Polar water was subject to an atmospheric temperature of 40° below zero, and could be cooled down to 27° without freezing; whilst the fresh water cooled by the ice in the trough could by no possibility have been less than 39°. The warmth of the solar heat, on the other hand, was greater than that of the warm end of the trough. At Aden, Mr. Latimer Clark blackened a thermometer and put it on a black surface, and on exposing it to the full rays of the sun it showed 215°. Of course, a part of the heat in the Mediterranean was continually passing off as vapour.

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